Symposium on Optical Fiber Measurements (SOFM 2002), Sep 24-26, 2002, Boulder, CO, NIST Special Publication 988, pp. 125-128

Four-state measurement method for polarization dependent wavelength shift

W.C. Swann, S.D. Dyer and R.M. Craig
National Institute of Standards and Technology
325 Broadway, Boulder, CO 80305
swann@boulder.nist.gov

ABSTRACT

We present a novel four-state method for measuring the polarization dependent wavelength shift (PDW) of a fiber Bragg grating. We show that measurement of the grating's wavelength for only four different polarization states is sufficient to completely determine the grating's PDW, and we show favorable comparison of four-states PDW measurement results with results obtained using the conventional "all states" technique.

1. Introduction

Use of Bragg gratings in wavelength division multiplexed (WDM) systems with ever decreasing channel spacing and in sensor systems with ever increasing accuracy requirements has placed stringent demands on the absolute accuracy and stability of a grating's wavelength. The two largest effects on a grating's wavelength: temperature and strain, are well understood and are often compensated by using active stabilization or athermal packaging. It is more difficult to control the grating's response to polarization, where the center wavelength of a grating can shift due to birefringence. In systems using unpolarized light, or where polarization is maintained using polarization maintaining (PM) fiber, this is not an issue. However, where polarized lasers are used or PM fiber is impractical, the grating's wavelength can wander with polarization. It is therefore important to know a grating's PDW if it is to be used in a system where wavelength accuracy is important. In this paper we define PDW as the maximum wavelength shift of the grating's spectrum that is induced by changes in polarization.

The most straightforward means of determining a grating's PDW is to monitor the wavelength shift of the grating's reflection (or transmission) spectrum while randomly varying the polarization of the light at the grating until the polarization state space has been reasonably well covered. A similar approach uses a large number of well-defined states uniformly distributed over the state space. Unfortunately, the large number of individual measurements these "all states" techniques require make them time consuming, and therefore impractical in a manufacturing environment. Furthermore these techniques can underestimate a grating's PDW; they will more closely represent the true PDW as the state space is more completely covered. The four-states technique described here allows a grating's PDW to be completely determined with only four measurements, and does not underestimate the PDW. This measurement technique can also be applied to the measurement of PDW for other types of wavelength-selective filters.

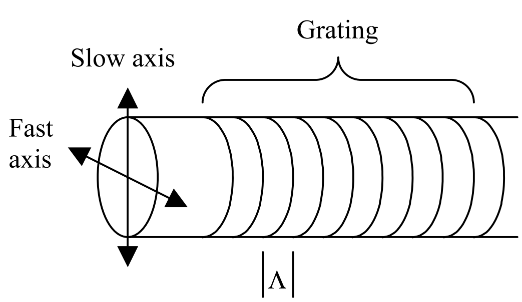

Figure 1: Birefringent fiber core in the region of the grating. Λ is the physical pitch of the grating.

2. Theory

The four-states technique assumes that PDW is caused by linear birefringence within the section of fiber containing the grating (Fig. 1). This birefringence may be caused by any combination of several mechanisms, most notable being fiber core geometry or strain asymmetry, asymmetry inherent in grating side writing techniques [1], or asymmetry due to the polarization of the writing light [2]. This birefringence results in polarization dependence of the Bragg grating's optical pitch, and thus the grating's center wavelength. Light polarized along the grating's fast axis sees a shorter optical pitch, and thus a shorter Bragg wavelength, than light polarized along the slow axis. For the purposes of this paper we define the fast and slow axes as the eigenaxes of the grating, and polarization states that lie on these axes as the grating's eigenstates. The difference between the grating's wavelengths for the two polarization eigenstates is the PDW of the grating. Arbitrarily polarized light has components along both the fast and slow axes, resulting in two spectral profiles shifted in wavelength with respect to each other. If the PDW is less than the grating's spectral width these two profiles overlap, resulting in a combined spectrum with a center wavelength somewhere between the fast axis and slow axis extremes. To determine the combined spectrum's wavelength shift verses polarization state, we modeled the grating's spectrum as a combination of two spectra shifted with respect to each other by the PDW shift, and weighed these spectra in proportion to the E field strength on the grating's eigenaxes for a given polarization state. We then observed the combined spectrum's wavelength shift as the model's polarization state was varied, and found that the shift varied sinusoidally

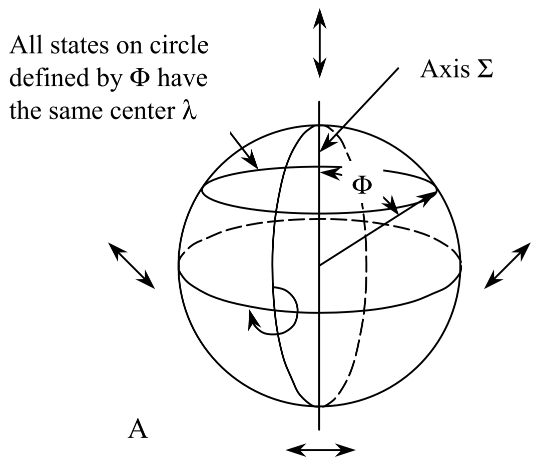

Figure 2A: Modified Poincaré sphere at the grating. The sphere is rotated with respect to conventional notation. The grating's mean wavelength is on the sphere's equator.

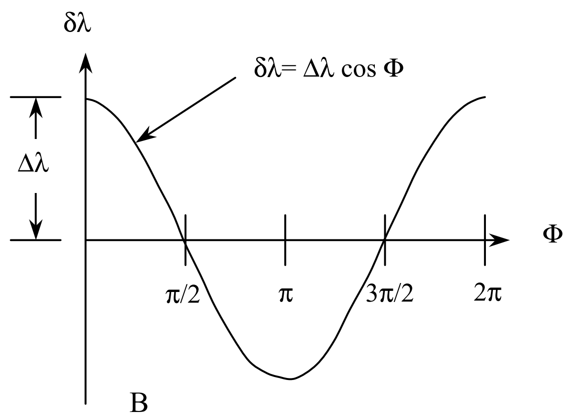

Figure 2B: Variation of wavelength shift $\delta\lambda$ with angle Φ. $\Delta\lambda$ is the maximum shift and occurs when the polarization is on either the grating's eigenaxes. The PDW for the grating is $2\Delta\lambda$.

as the polarization evolved from the grating's slow axis to its fast axis eigenstate [Fig. 2]. In theory a grating's PDW can be determined by finding the shift in the grating's center wavelength for the two polarization eigenstates. In practice determining the grating's eigenaxes is difficult, and furthermore any polarization state launched into the fiber may transform into some other, arbitrary state at the grating. With a suitable choice of four input polarization states, however, and assuming the unitary transformation between these input states and the states at the grating (i.e. the angular relationship between the states is preserved), in the absence of PDL and depolarization in the grating, we can determine the grating's PDW as follows.

To discuss the theory behind the four-states technique we enlist the following conventions [Figs. 2 and 3]. We use modified Poincaré spheres S and S′, respectively to describe the polarization states s_i and s_i' at the input end of the fiber and at the grating. Our modified Poincaré sphere notation maps center wavelength rather than power onto the sphere's surface. Σ' is an axis running through the grating's eigenstates on the sphere S′, and Φ_{si}' is the angle between Σ' and polarization state s_i' on S′. For the four input states we choose two orthogonal states (for example s_1 = linear horizontal and s_2 = linear vertical) and two states displaced by 90° on S from the first two states and from each other (for example s_3 = +45° linear and s_4 = right circular). An example showing this choice of four input states is shown in Fig. 3. Notice that the four states laid out on the sphere resemble three mutually perpendicular unit basis vectors together with a fourth vector directed opposite to one of the other three. These four input states s_i will evolve to four other states s_i' at the grating.

For each state s_i launched into the fiber we measure the center wavelength λ_{si}' of the grating's reflection peak. From the average of wavelengths λ_{s1}' and λ_{s2}' given by the two orthogonal polarization states, we determine a mean wavelength $\lambda_{mean} = (\lambda_{s1}'+\lambda_{s2}')/2$. From this we determine $\delta\lambda_{si}' = \lambda_{si}'-\lambda_{mean}$, where $\delta\lambda_{si}'$ is the shift from the mean wavelength for polarization state s_i'. Now, from Fig. 2 we see that $\delta\lambda_{si}'=\Delta\lambda\cos\Phi_{si}'$, where $\Delta\lambda$ is the difference between the maximum wavelength and λ_{mean}. Disregarding one of the two orthogonal states, and taking $\cos\Phi_{si'}$ as direction cosines [3] between Σ' and s_i', we use the relationship $\cos^2\Phi_{s2} + \cos^2\Phi_{s3} + \cos^2\Phi_{s4} = 1$ [4] to get $[(\delta\lambda'_{s2})^2 + (\delta\lambda'_{s3})^2 + (\delta\lambda'_{s4})^2]^{1/2} = \Delta\lambda$. (We could just as easily use $\cos\Phi_{s1}$ instead of $\cos\Phi_{s2}$, and $\delta\lambda_{s1}$ instead of $\delta\lambda_{s2}$.) The PDW for the grating is $2\Delta\lambda$.

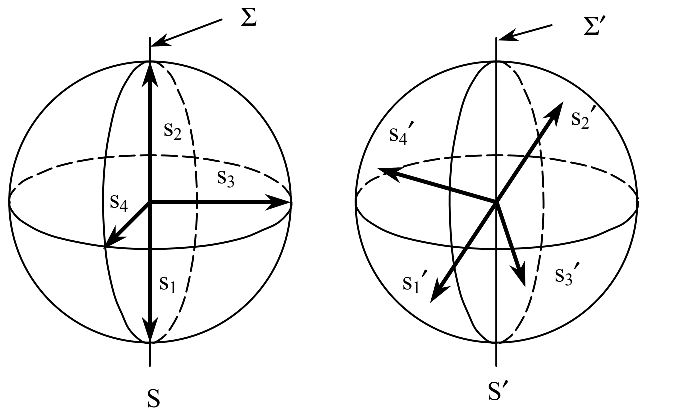

Figure 3: Poincaré spheres S at the input end of the fiber and S′ at the grating, showing evolution of input states s_i to states s_i'.

3. Experimental Results

We measured three gratings with different amounts of PDW using the four-states technique, and compared the results to "all states" measurements of the same gratings. For the all states measurement we chose 26 states uniformly distributed about the sphere. Each state's measurement entailed setting a tunable diode laser's polarization to the desired state using a pair of waveplates and scanning the laser's wavelength across the grating's reflection spectrum while monitoring the wavelength with a wavelength meter. For each polarization state, we fitted the resulting plot of reflectance versus wavelength over the wavelength values ranging between the reflection spectrum's FWHM points using a fourth order polynomial fit. We found that the grating profiles were slightly asymmetric, leading to a slight difference between the profile's center and extremum wavelengths. Because the profile's extremum is better defined than its center, we used the shift in the extremum of the fit vs. polarization state to determine the grating's PDW.

For the all-states technique we took the difference between the maximum and minimum wavelength returned by the 26 scans as the PDW. This technique has the potential of under-determining the PDW by up to about 10 %, as dictated by how closely the launched states approach the fast and slow axes at the grating. In addition to this there is an uncertainty in the all-states PDW of $\sqrt{2}\sigma$, where σ is the standard uncertainty in the extremum wavelength given by the polynomial fit. For the four-states technique we determined the PDW as described in the previous section, and we calculate the PDW uncertainty to be about 2.5σ. Both of these uncertainties are given using standard propagation of errors formalism.

The results for the three gratings are shown in Table 1. We ran two trials on gratings 1 and 2, and four trials on grating 3 for both the four-states and all-states technique. Gratings 1 and 2 have a standard uncertainty σ in their extrema of about 0.25 pm, leading to an uncertainty of about ± 0.6 pm for the four-states PDW, and about 0.4 pm for the all-states PDW. Grating 3 has a standard uncertainty σ of about 0.14 pm, leading to a predicted uncertainty in the four-states PDW of about 0.4 pm and in the all-states PDW of about 0.3 pm. For gratings 1 and 2 the 26-states results are lower than the four-states results by up to 8%, as expected for reasons stated above, and the four-states and all-states results agree for grating 3. Also, the results for the two trials agree to within the expected uncertainties, indicating repeatability of the measurements.

Table 1: Comparison of 4-state and 26-state PDW results

Grating	Trial	26-states PDW (pm)	4-states PDW (pm)
1	1	30.7(4)	32.3(6)
	2	29.8(4)	31.6(6)
2	1	8.1(4)	8.8(6)
	2	7.9(4)	8.5(6)
3	1	1.0(3)	0.9(4)
	2	1.1(3)	1.0(4)
	3	1.1(3)	0.9(4)
	4	1.1(3)	1.3(4)

5. Conclusion

We have presented a four-states technique for measuring the polarization dependent wavelength shift of a fiber Bragg grating. Although we describe measurement of a relatively narrow grating, this technique should be applicable to measuring shifts in the band-edge of WDM channel filter or similar wide-bandwidth gratings. Furthermore, with suitable reference detectors, it could be generalized to include simultaneous measurement of polarization dependence in the reflectance, transmittance, or loss of the grating.

References:

1. A.M. Vengsarker, Q. Zhong, D. Inniss, W.A. Reed, P.J. Lemarie and S.G. Kosinski, "Birefringence reduction in side-written photoinduced fiber devices by a dual-exposure method," Opt. Lett. **19**, pp. 1260-1262 (1994).

2. T. Ergodan and V. Mizrahi, "Characterization of UV-induced birefringence in photosensitive Ge-doped silica optical fibers," J. Opt. Soc. Am. B **11**, pp. 2100-2105 (1994).

3. G. Arfkin, *Mathematical Methods for Physicists*, third edition (Academic Press 1985), pp. 4, 191.

4. M.R. Spiegel, *Mathematical Handbook*, Shaum's Outline Series (McGraw-Hill 1968), pp. 46.